# Optical Properties of Mineral Particles and the Inversion of Ocean Surface Reflectance In Coastal Waters

Dariusz Stramski
Marine Physical Laboratory
Scripps Institution of Oceanography
University of California at San Diego
La Jolla, CA 92093-0238
phone: (619) 534 3353 fax: (619) 534 7641 e-mail: stramski@mpl.ucsd.edu
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## LONG-TERM GOALS

The long-term goal of this research is to develop the base of knowledge necessary to:
(i) understand the magnitudes and variability of the inherent and apparent optical properties of the ocean;
(ii) predict the inherent absorption and scattering properties of sea water and the apparent properties such as remotely sensed reflectance, given the types and concentration of suspended particles;
(iii) retrieve the concentration of optically significant constituents of sea water from reflectance measurements.

## SCIENTIFIC OBJECTIVES

Although mineral particles are a major optical component of coastal ocean, very little work has been done on characterizing the absorption and scattering properties of the various mineral particle assemblages occurring in marine environments. My goal for this past fiscal year was to begin a study of the optical properties of mineral particles. Specific objectives were to:
(i) expand single-particle optical property database by determining optical cross-sections and scattering phase functions for generic mineral particles, organic detrital particles, and air bubbles;
(ii) conduct a field experiment for the purpose of measuring the inherent and apparent optical properties within a marine environment that exhibits dramatic variations in the optical water type, from the mineral-dominated to phytoplankton-dominated type.

## APPROACH

In past reporting periods, my efforts to develop a database of single-particle optical properties for marine microorganisms were described. This development was addressed through a combination of laboratory measurements of various microbial cultures and modeling of particle optics (Stramski and Mobley, 1997). The current microbial database includes the spectral absorption and scattering cross-sections and scattering phase functions for 18 microbial components, each representing a particular class or species of microorganisms. This information was derived from studies of 24 species, strains, or taxonomic groups of microorganisms ranging in size from viruses to small microplankton (Stramski et al., 1998). In this reporting period, the database was expanded to include three other important components: generic mineral particles (polydisperse particles with a high refractive index), generic organic detrital particles (polydisperse particles with a low refractive index), and generic air bubbles.

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The estimates of optical cross-sections and phase functions for these three components were obtained from Mie scattering calculations based on approximations to the size distributions and refractive index of these components. The biogenic detritus was modeled as an assemblage of particles with wavelength-independent real part of refractive index of 1.04 (relative to water), diameters ranging from 0.05 to 500 μm, and the Junge–type size distribution with a slope of –4. The spectrum of the imaginary part of refractive index was derived from microspectrophotometric data on individual detrital particles (Iturriaga and Siegel, 1989) using an inverse model of particle absorption. The mineral particles have the same characteristics except that the refractive index is 1.18. Finally, the gas bubbles were assumed to obey the Junge-type distribution within the diameter range from 20 to 500 μm, and their refractive index is 0.75 (with no absorption). In this approach, the optical quantities are determined in the spectral region from 350 to 750 nm at 1-nm intervals. The scattering phase function is determined at 1-degree intervals in the scattering angle (for angles > $5^o$) and at 0.1-degree intervals for smaller scattering angles.

For objective (ii) I participated in the cruise on *R/V Oceania* in July 1998. The study area included the coastal waters of Spitsbergen and the Greenland Sea. This field campaign was part of the polar research program of the Polish Academy of Sciences, and my participation in the cruise was supported by NASA. The cruise provided an excellent opportunity to measure the optical properties over a broad range of water types, from mineral-dominated waters in Kongsfjord (northwestern Spitsbergen) to phytoplankton-dominated waters in the Greenland Sea. The observational program consisted of *in-situ* measurements of spectral downwelling irradiance and upwelling radiance (SPMR, Satlantic), beam attenuation at two wavelengths, 488 nm and 660 nm (C-Star, WetLabs), backscattering at six wavelengths (Hydroscat-6, HobiLabs), chlorophyll fluorescence (WetStar, WetLabs), temperature and salinity (CTD, SeaBird), and on-board analyses of discrete water samples for particulate absorption spectra and chlorophyll concentration. Samples for particulate organic carbon and mineralogical analysis were also taken.

**WORK COMPLETED**

Calculations of the optical cross-sections and phase functions for the generic mineral particles, organic detritus and air bubbles were completed. The results were incorporated into the single-particle optical property database. The paper describing this expanded database was completed and will be presented at the Ocean Optics XIV Conference in Hawaii in November 1998 (Stramski et al., 1998). The use of the database in radiative transfer modeling is described separately in the annual report by Mobley and Stramski.

Cruise preparations including integration of several optical instruments into our multi-sensor datalogger system based on SeaBird’s SBE 25 were done. The observational program during the Arctic cruise was successfully completed. Basic processing of radiometric data (assessment of data quality, preliminary data reduction, conversion to physical units, calculation of the apparent optical properties) has been finished. Processing of data on the inherent optical properties is in progress.

In addition, during the reporting period I published a paper on the optical properties of carotenoid-rich marine bacteria (Stramski and Kiefer, 1998) and I completed a paper on the new approach for estimating carbon and chlorophyll content in individual planktonic cells from optical determination of the refractive index (Stramski, in press). These contributions result from work described in the past reporting periods.  Also, as a co-author I made a contribution to two other publications (Bogucki et al., 1998; Berwald et al., 1998).

## RESULTS

Mie scattering calculations showed that an average mineral particle derived from the generic assemblage of high refractive index particles has approximately 4.5-fold higher spectral scattering cross-sections and 28-fold higher backscattering cross-sections, if compared to an average, low-index organic detrital particle (Fig. 1).  Comparison of scattering phase functions also show significant differences; the phase function for the average mineral particle is less steep than for the detrital particle  (Fig. 3).  The results also show that the Petzold particle phase function is much steeper than the phase function for minerals.  Finally, assuming that air bubbles less than 20 μm in size have no significant influence on light scattering by sea water, the bubbles exhibit the most forward peaked scattering phase function among those compared in Fig. 3.  In addition, the scattering and backscattering cross-sections for bubbles show no spectral dependence (Fig. 2).

The inherent and apparent optical properties measured in turbid, mineral-dominated waters of Kongsfjord (northwestern Spitsbergen) are shown in Figures 4 and 5.  For comparison, data from clear, phytoplankton-dominated waters off Spitsbergen are also shown.  Kongsfjord is characterized by large discharge of mineral particles from glacier runoff.  Differences in the composition of mineral assemblages between different parts of the fjord lead to some variation in water color within the fjord (from reddish to yellowish/grey).  The particulate backscattering coefficient $b_b$ in these mineral-rich waters is one to two orders of magnitude higher than in clear, phytoplankton-dominated waters.  The spectral shape of $b_b$ can also differ considerably between mineral-dominated and phytoplankton-dominated waters.  One example in Fig. 4 shows a distinct maximum of $b_b$ at about 590 nm.  This feature is also seen in the reflectance spectrum, $L_u/E_d$ (Fig. 5).  Reflectance exhibits distinctly different spectral shapes and magnitudes if waters are rich in minerals as a result of combined effects of absorption and backscattering by these particles.  Importantly, my measurements provide evidence that significant variations in spectral reflectance or ocean color can occur because of changes in backscattering spectra, which are associated with varying mineral composition of particulate assemblage (see upper panels in Fig. 5).  Comparison of minerals from Kongsfjord with Saharan dust indicate that changes in mineral composition can also be responsible for significant variations in the spectral shape of absorption (Fig. 6).

## IMPACT/APPLICATIONS

The application of ocean color remote sensing to coastal waters is contingent upon the knowledge of the spectral optical properties of the various organic and mineral components present in such waters. To succeed in this application a coordinated research is required, in which the development of reflectance inversion algorithms is conducted in tandem with determinations of the optical properties of aquatic components.  Although *suspended minerals* play a major role in coastal optics, these particles have been among the *least studied* components.  The major impact of this project is to fill the gap in our understanding of how the various mineral particles suspended in sea water absorb and scatter light, and how such particles affect the apparent optical properties of the ocean including remotely sensed reflectance. Through the development of a quantitative characterization of the optical properties of mineral particles, this project will lead to a detailed understanding of the roles played by various types of sea water components in oceanic optics, which is a prerequisite to advancing numerous applications associated with optical measurements including ocean color remote sensing.

The addition of generic mineral particles to my single-particle optical property database will allow us the simulate the bulk optical properties of particulate assemblages more realistically than the previous versions of the database. The major significance and applicability of the database stems from the fact that it provides a foundation for a new generation of optical models that will describe the bulk inherent optical properties of natural waters as a function of detailed composition of water, or more specifically, as a function of concentrations of various types of particles. This approach will advance optical models beyond their present overly simplified parameterization, which usually involves just one parameter, the chlorophyll concentration. In another ONR-sponsored project (see the annual report by Mobley and Stramski) we describe how powerful a combination of the database and radiative transfer modeling is in the study of oceanic optics. The significance of the initial results from field experiments is that they indicate that the optical complexity of coastal waters requires a multi-component description, in which suspended minerals are regarded as a distinct component with variable absorption and scattering properties.

## TRANSITIONS

Parts of the single-particle optical property database have been made available to several researchers, S. Ackleson at ONR, R. Leathers at NASA Stennis Space Center, R. Stavn at the University of North Carolina, and A. Morel and A. Bricaud in France. R. Leathers has recently published a paper on the inverse reflectance model based on neural networks that were trained using my database (Leathers, 1998). The entire database was also made available to C. Mobley for the purpose of carrying out our collaborative studies described in a separate report.

## RELATED PROJECTS

The database of single-particle optical properties is directly incorporated in the ONR-sponsored project which is aimed at studying influences of various types of particles on oceanic optics through the application of radiative transfer modeling (see report by Mobley and Stramski). Participation in the Arctic cruise, which allowed me to collect optical data in mineral-dominated coastal waters of Spitsbergen (Kongsfjord), was sponsored by NASA. The goal of my NASA project is to make optical measurements in the Greenland and Norwegian Seas in support of MODIS ocean color validation program. A comprehensive study of mineral-rich waters of Kongsfjord is of direct importance to this project and was not planned in the NASA project.

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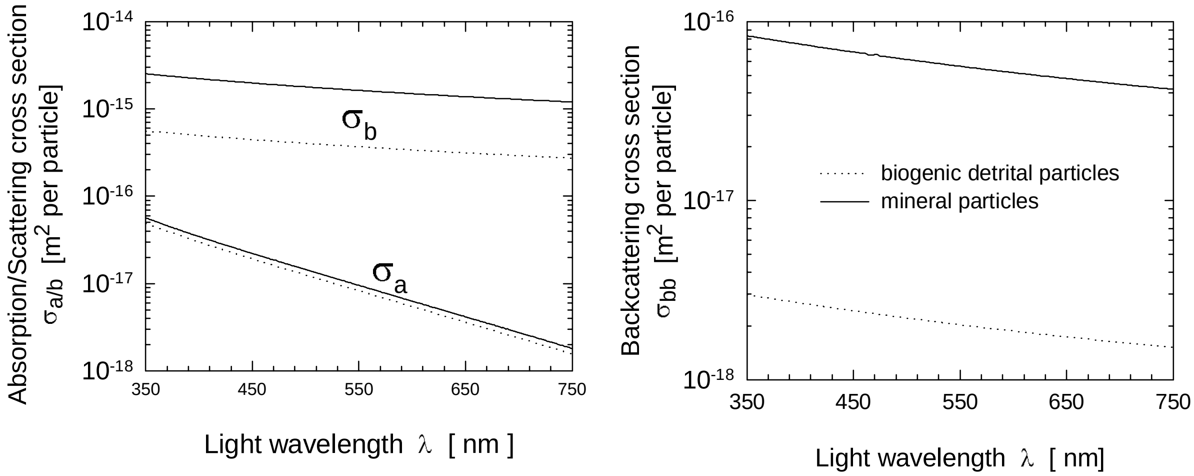


Fig. 1. Left-hand panel: Absorption ($\sigma_a$) and scattering ($\sigma_b$) cross sections for generic assemblages of biogenic detrital particles (dotted lines) and mineral particles (solid lines). Right-hand panel: Backscattering cross sections of biogenic detritus and mineral particles.

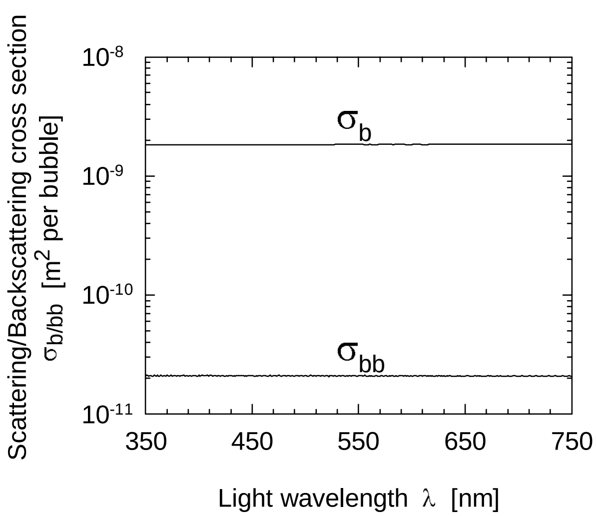


Fig. 2. Scattering ($\sigma_b$) and backscattering ($\sigma_{bb}$) cross sections for generic assemblage of gas bubbles.

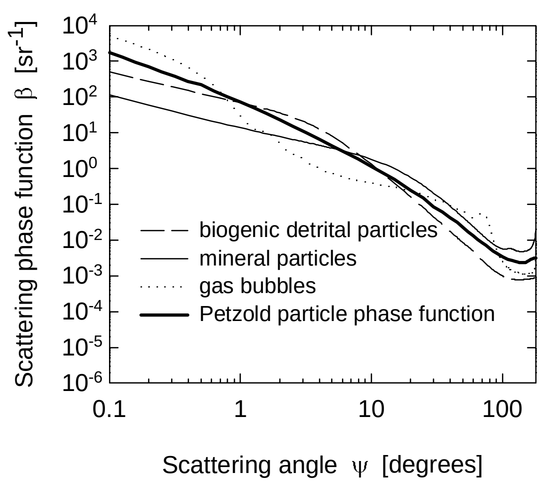


Fig. 3. Comparison of scattering phase functions (at 550 nm) of derital particles, mineral particles, and gas bubbles with the Petzold particle phase function.

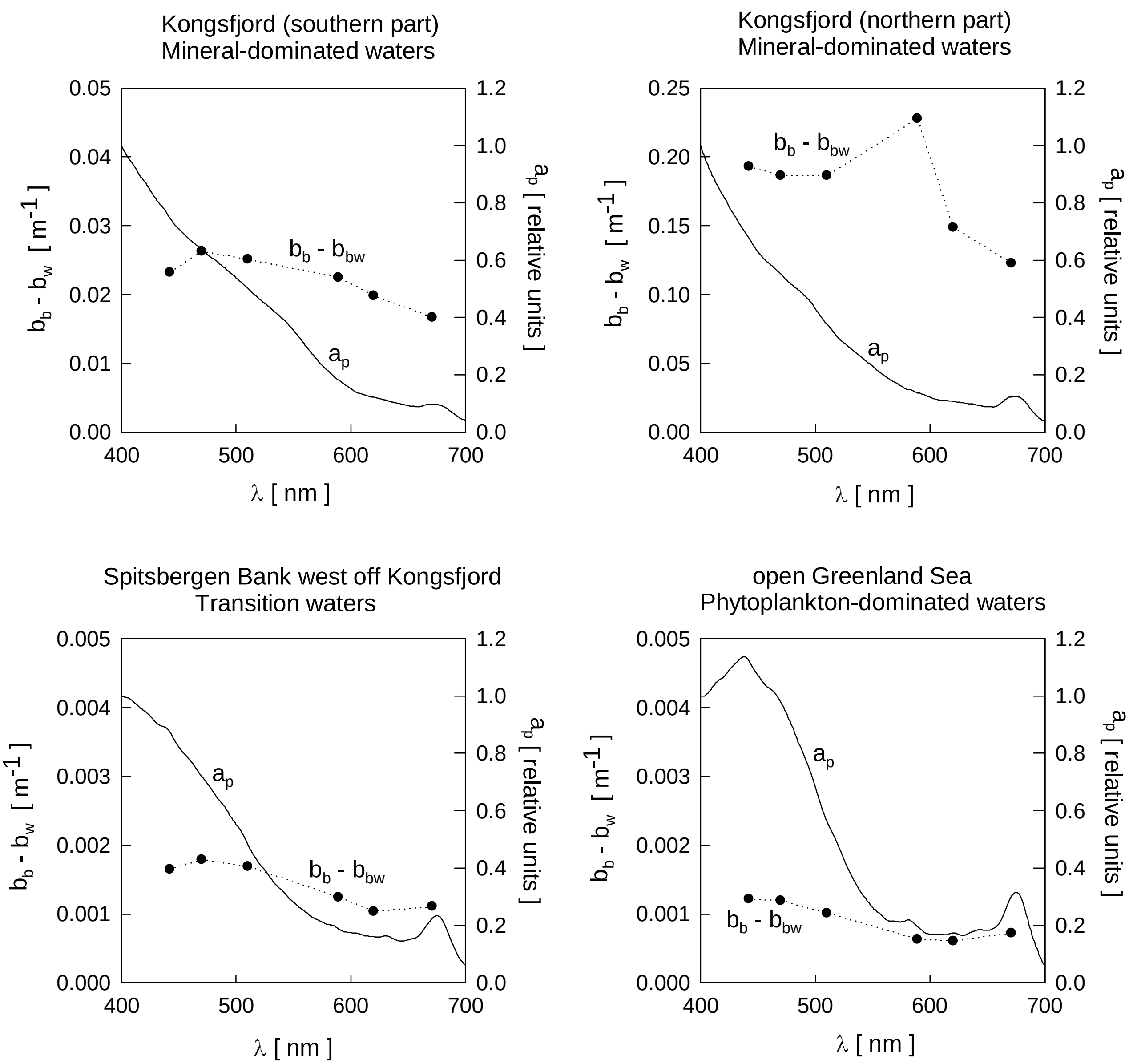


Fig. 4. Comparison of the inherent optical properties measured just below the sea surface (the particulate backscattering coefficient, $b_b$-$b_{bw}$, and the particulate absorption coefficient, $a_p$) for mineral-dominated waters in Kongsfjord, transition waters with significant concentration of phytoplankton, and phytoplankton-dominated waters in the open Greenland Sea.

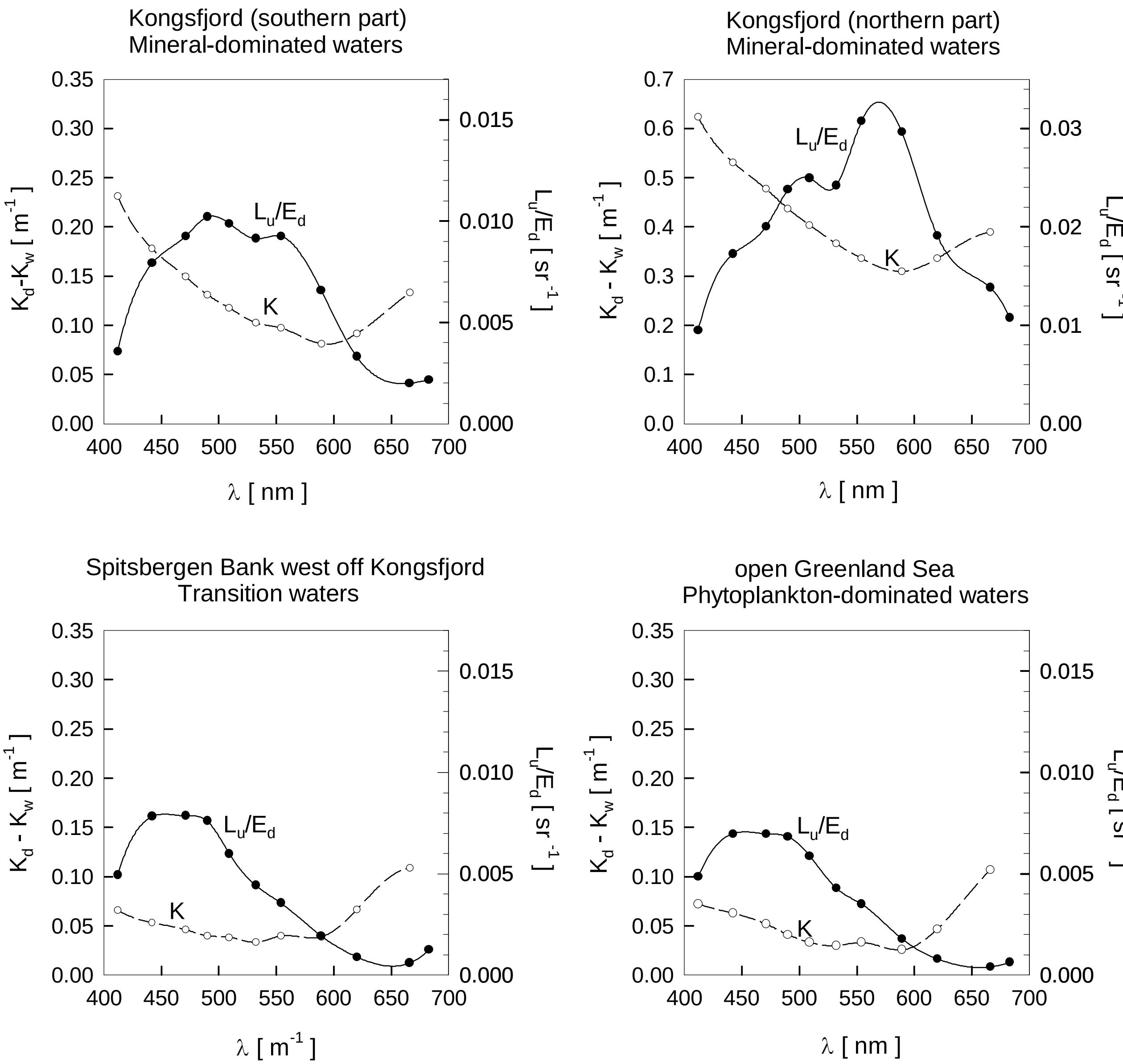


Fig. 5. Comparison of the apparent optical properties measured just below the sea surface (the reflectance, $L_u/E_d$, and the diffuse attenuation coefficient for downwelling irradiance, $K_d$-$K_w$) for mineral-dominated waters in Kongsfjord, transition waters with significant concentration of phytoplankton, and phytoplankton-dominated waters in the open Greenland Sea.

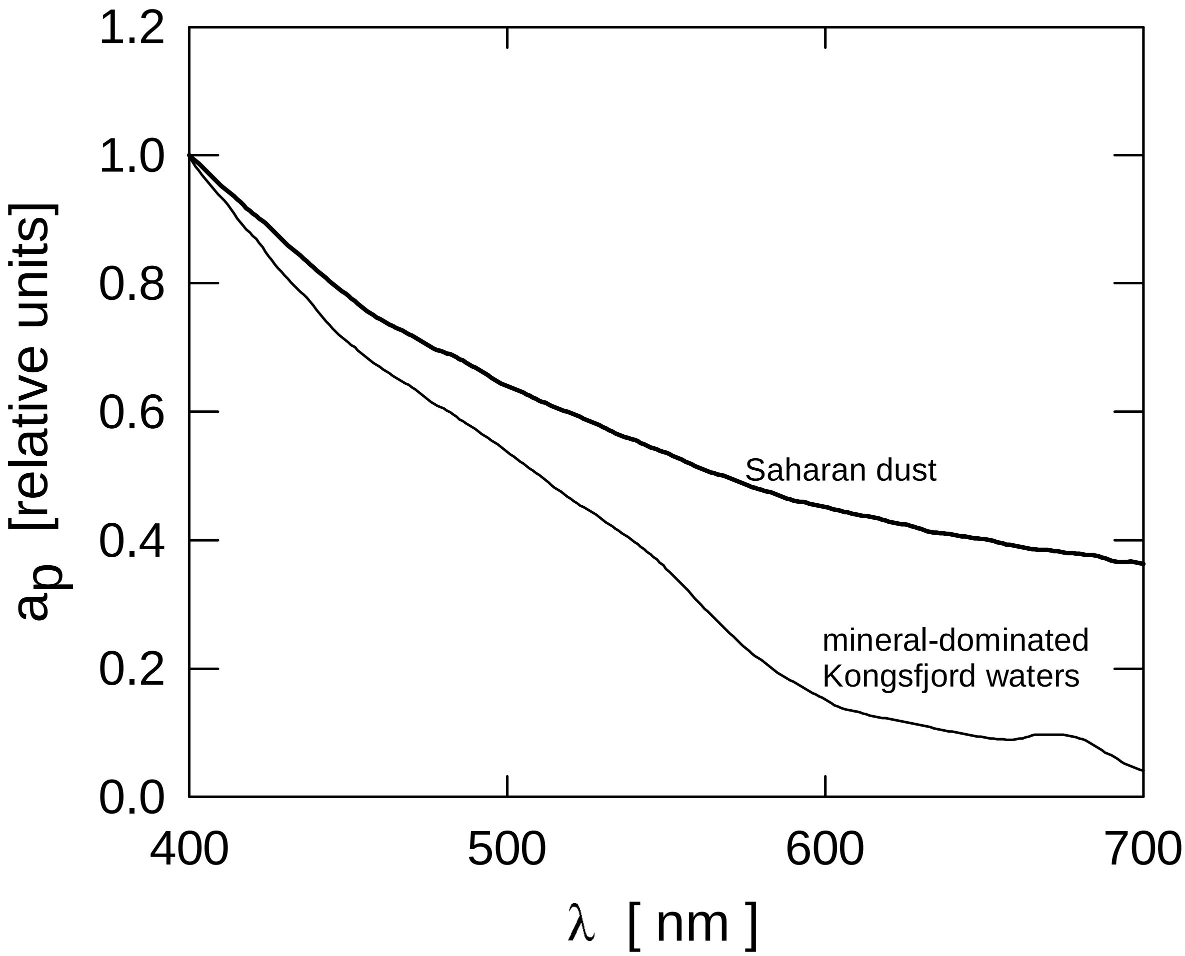


Fig. 6. Comparison of the normalized absorption spectra of particles for mineral-dominated waters of Kongsfjord (northwestern Spitsbergen) and for Saharan dust. Samples of Saharan dust were collected in the coastal zone of the Mediterranean Sea in the southern France during the "red rain" event. The measurements were made using a bench-top double-beam spectrophotometer with appropriate geometric configuration.